Radiation study of FPGAs with neutron beam for COMET Phase-I

Yu Nakazawa[1], Yuki Fujii[2], Eitaro Hamada[2], MyeongJae Lee[3], Yuta Miyazaki[4], Akira Sato[1], Kazuki Ueno[2], Hisataka Yoshida[1], Jie Zhang[5]

[1]Osaka University, Osaka, Japan; [2]KEK, Tsukuba, Japan; [3]IBS/KAIST, Daejeon, Korea; [4]Kyushu University, Fukuoka, Japan; [5]IHEP, Beijing China

Introduction

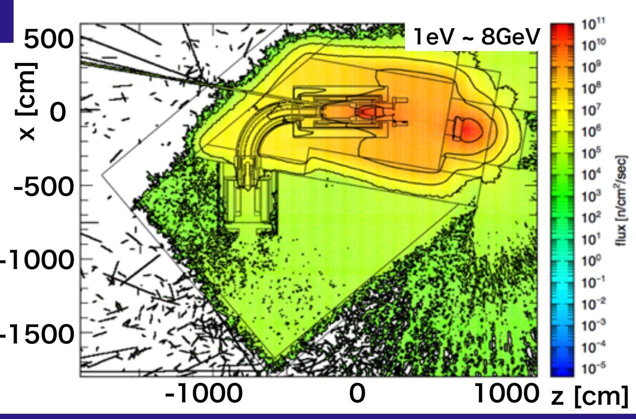
The COMET Phase-I experiment at J-PARC plans to search for muon to electron conversion using the highest intensity muon beam in the world. A proton beam of 8 GeV, 3.2 kW will be stopped on a graphite target to produce muons and it makes a high radiation environment. We plan to use Virtex-5, Artix-7 and Kintex-7 released by Xilinx Inc. for the readout electronics. Due to the high radiation level, we expect to have high frequency of soft errors. Therefore several radiation tests were performed. Here the results of soft error rates from a series of neutron irradiation tests on different FPGAs are presented.

Neutron fluence in COMET Phase-I

Neutron fluence : 1.0 ×10^{12} neutron/cm^2 (1 MeVeq)

- Measurement time : 150 days
- Safety factor : 5 - 10 (model dependent)
  - Soft error cross section depends on $E_{neutron}$.
  - Neutron fluence depends on the location.

PHITS simulation

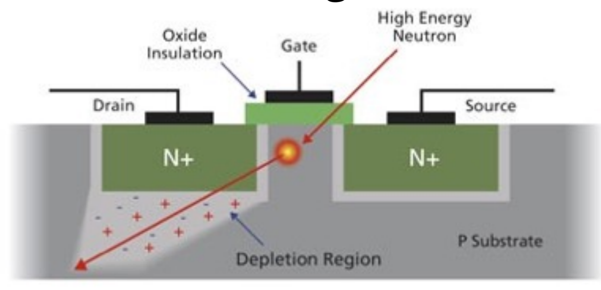


Neutron damage

Due to the neutron-nuclear interaction in a semiconductor, a charged particle can be generated. This particle creates electron-hole pairs that affect logic in FPGA.

- Critical area for soft error
  - Configuration RAM (CRAM)
  - Block RAM (BRAM)
- Error type
  - Single Event Upset (SEU)
  - Multi Bit Errors (MBE)

Schematic diagram of SEU

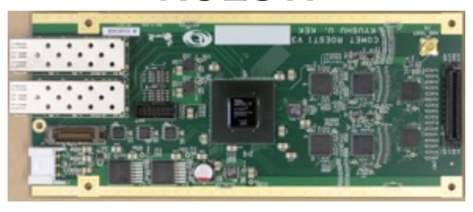


ref. Cosmic rays damage automotive electronics, http://www.embedded.com/print/4011077

Front-end electronics

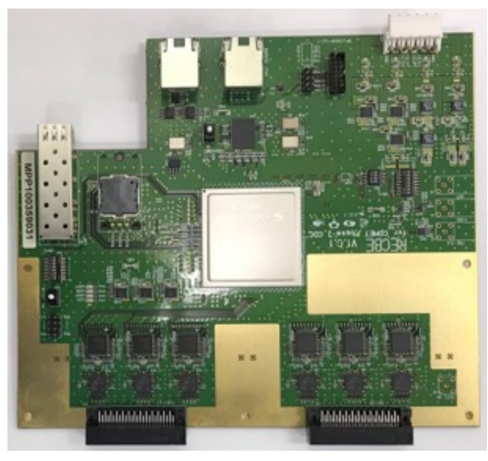
4 types of front-end electronics are placed on the detector region. FPGAs are used for digital signal processing from detectors or other electronics.

ROESTI



FCT

RECBE



COTTRI

- RECBE
  - Cylindrical drift chamber
  - TDC with 1 nanosecond resolution
- ROESTI
  - Straw chamber and Calorimeter
  - 1 GSPS DRS4 + ADC
- COTTRI
  - Primary trigger generator
- FCT
  - Distributor for clock and trigger
  - Receiver of busy signal from FE

	FPGA	FPGA Size [mm]	CRAM used [Byte]	BRAM used [Byte]
RECBE	Virtex-5 (XC5VLX155T-1FFG1738C)	35 x 35	5,380,288	2,934,000
ROESTI	Artix-7 (XC7A200T-2FBG676C)	27 x 27	9,730,652	1,105,920
COTTTRI	Artix-7 (XC7A200T-2FFG1156C)	35 x 35	9,730,652	131,072
FCT	Kintex-7 (XC7K160T-2FFG676C)	27 x 27	6,692,572	18,600

ref. Virtex-5 Family Overview (Xilinx Inc.), 7 Series FPGAs Data Sheet: Overview (Xilinx Inc.)

Auto-recovery system

Most of the soft errors can be repaired by error detection/correction schemes. However the schemes excluding Triple Modular Redundancy cannot repair MBEs thus the firmware needs to be downloaded when an unrecoverable soft error (URE) occurs.

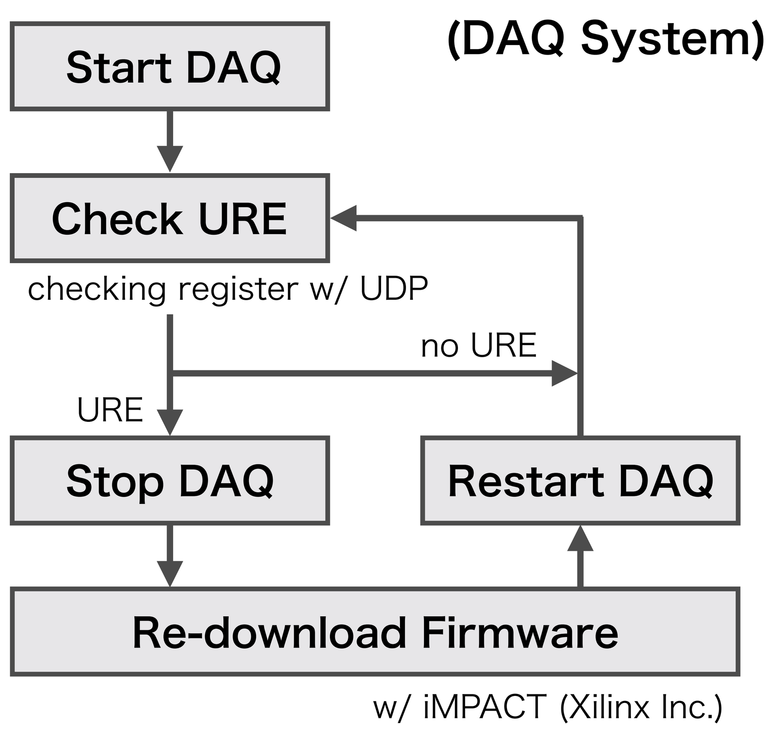
Recovery system in FPGA

- Detection only
  - Cyclic Redundancy Check (CRC)
- Detection/correction
  - CRAM : SEU Contoroller for Virtex-5
    Soft Error Mitigation (SEM)
  - BRAM : Error Correction Code (ECC)
    Triple Modular Redundancy (TMR)

Definition of URE

- CRAM MBE
- Connection error
- Strange register value
- CRC error

Automatic re-downloading function (DAQ System)



We implemented the above schemes on the firmwares.

ref. SEU Strategies for Virtex-5 Devices, Soft Error Mitigation Controller v4.1, ECC v2.0 (Xilinx Inc. for all doc.)

Neutron irradiation tests

TANDEM @Kobe Univ. (Japan)

Beam : 3 MeV Deuteron

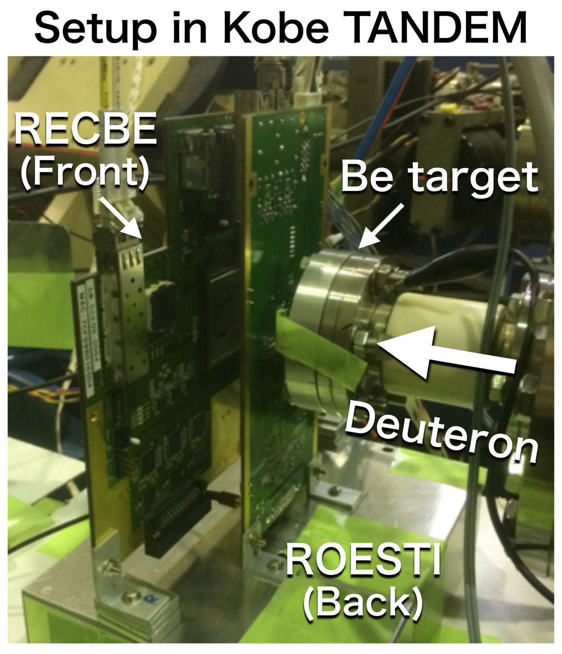
Target : Be (ϕ20 mm)

Neutron energy : 2 MeV (max. 7 MeV)

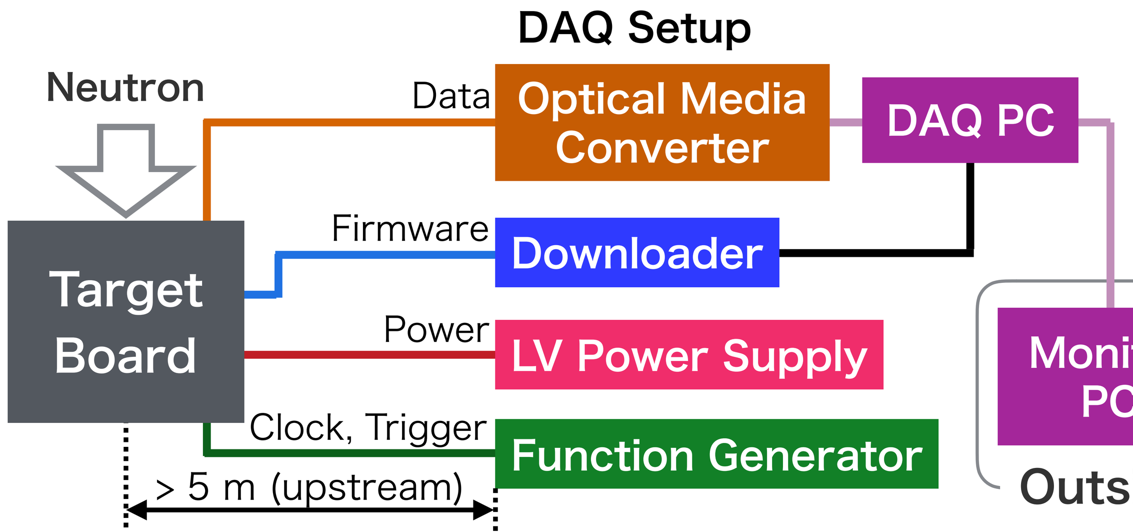
Neutron flux : (1.9±0.2) MHz/cm^2/μA (Preliminary)

- @10 cm from Be target on beam axis
- Measured by CR39
- Including distance uncertainty and angular uncertainty
- Another measurement result : 5.1 MHz/cm^2/μA (under analysis)

Setup in Kobe TANDEM



DAQ Setup



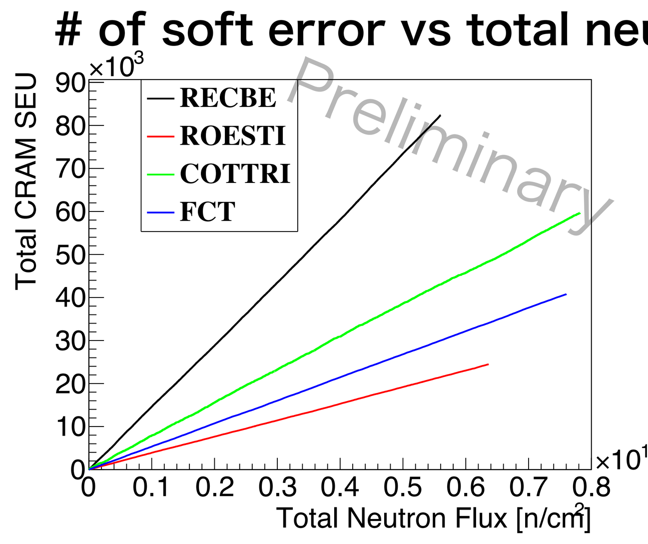
Evaluation

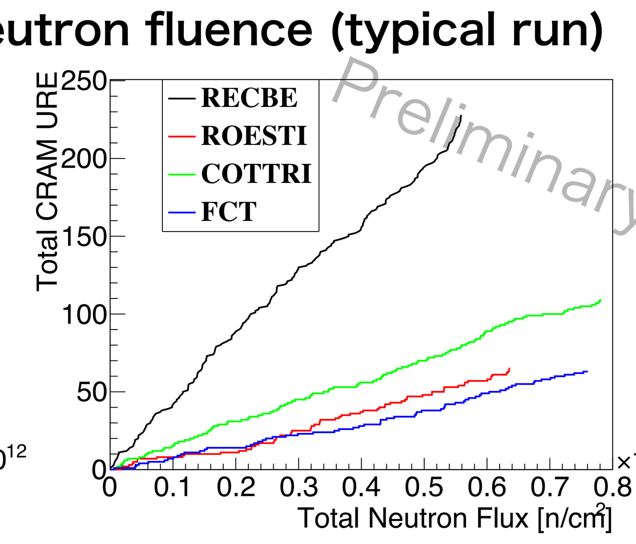
- Soft error rate
  - CRAM SEU & URE
  - BRAM SEU & MBE
- Recovery System
- TMR operation

Results

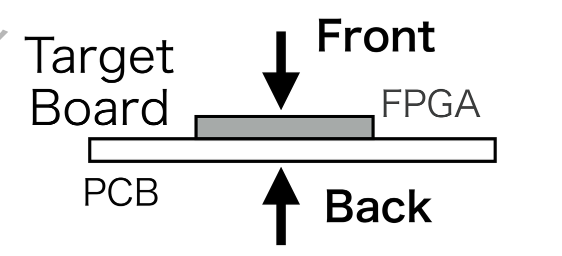
- Total neutron fluence : > 1.0×10^{12} neutron/cm^2.
- Auto-recovery systems worked and info. of soft errors could be taken.
  - Comparison between w/ and w/o neutron beam
- By checking TMR output, we confirmed that TMR worked.
  - Comparison between TMR and non-TMR firmware

\# of soft error vs total neutron fluence (typical run)





Definition of incident angle

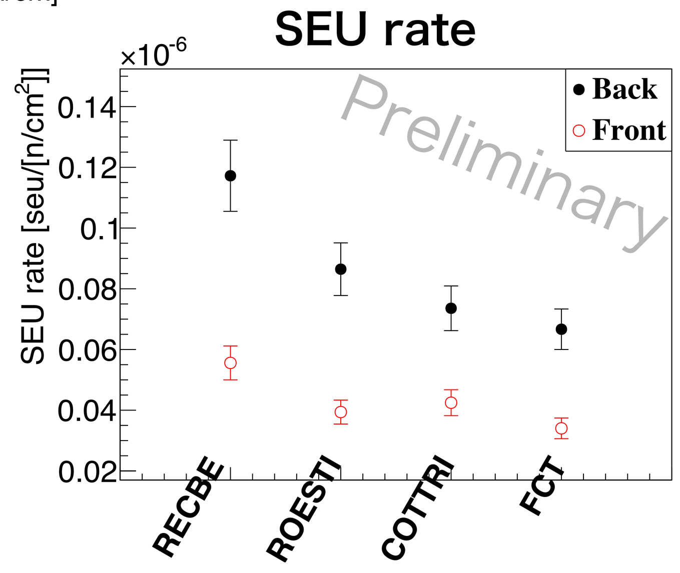


Back side	CRAM		BRAM		CRAM URE rate in COMET [ure/hour]
	SEU [seu/[n/cm^2]]	URE [ure/[n/cm^2]]	SEU [seu/[n/cm^2]/KB]	MBE [mbe/[n/cm^2]/KB]	
RECBE	(1.2±0.1)×10^{-7}	(3.5±0.4)×10^{-10}	(1.8±0.2)×10^{-10}	(2.5±0.3)×10^{-12}	1/10
ROESTI	(8.6±0.9)×10^{-8}	(3.1±0.5)×10^{-10}	(1.9±0.2)×10^{-11}	O(10^{-14})*	1/12
COTTRI	(7.4±0.7)×10^{-8}	(1.4±0.2)×10^{-10}	(1.8±0.3)×10^{-11}	(3.6±1.0)×10^{-12}	1/26
FCT	(6.7±0.7)×10^{-8}	(1.5±0.2)×10^{-10}	(2.2±2.5)×10^{-11}	O(10^{-14})*	1/25

- No permanent damage
- It was confirmed that when URE occurred,
  - URE was detected by auto-recovery systems.
  - The firmware was automatically re-downloaded.
- Incident angular dependence
  - It was found that front side was more tolerant than back side.

* # of error is too small.

SEU rate



Conclusion & Prospect

- We have completed implementations of auto-recovery systems and measurements of soft error rates.
  - FPGA dependence of CRAM SEU rate was measured. 7 series FPGAs are more tolerant than Virtex-5.
- Dead time by soft errors can be suppressed by auto-recovery systems.
- Error flags will be added to data because it takes a few milliseconds to fix CRAM SEU.
- Quantitative evaluations of TMR will be done.

	RECBE	ROESTI	COTTRI	FCT
Re-download time [sec]	23	37	75	26
Dead time**	0.061%	0.086%	0.079%	0.029%

** (re-download time)/(measurement time) in COMET Phase-I

Frontier Detectors for Frontier Physics: 14th Pisa Meeting on Advanced Detectors, La Biodola, Isola d'Elba, Italy, May 27th - June 2nd 2018